VNC Coronagraph Concept for AFTA Telescope

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Science Goals and Flow Down

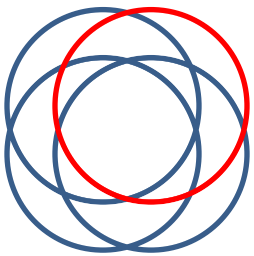
- AFTA coronagraph is NOT TPF-C.
  - 2.4m apeture (not 3*8m)
  - Jupiter, rather than Earths
    - Detect 10^{-9} contrast planets
      - Optical contrast ~ 10^{-9}
      - After post det speckle subtraction < $2x10^{-10}$
  - Spectra of known planets, rather than search for Earths + spectra
    - Want high throughput over a small field of view (Complete "circular" dark hole less important) ~99% of time spent getting spectra ~1% on search.
  - **AFTA has a large central obscuration and 6 spiders**
    - This has led to a slew of "New" inventions, PIAA/CMC, ACAD, Vortex#3 etc.
    - While a great deal of progress has been made in experimental demonstration of coronagraphs for **unobscured** apertures. These **NEW** inventions have not been tested in the lab, and in some cases are not yet conceptually complete.
    - The **NEW** inventions in many cases are absolutely needed ie, the coronagraph concept **doesn't work without the NEW** invention.
  - The experimental work on filled aperture coronagraphs have provide a wealth of technology tools to enable an AFTA coronagraph. But virtually every AFTA coronagraph is a **new Concept**.

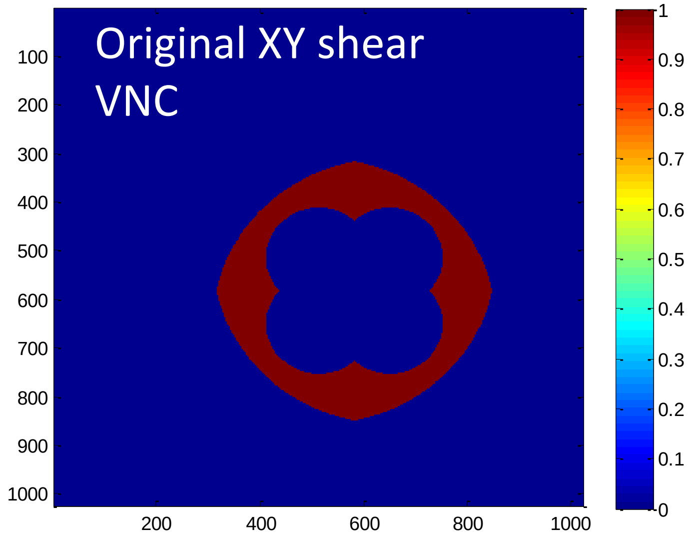
Search for Known Jupiters

- Jupiter mass planets can be (have been) discovered with ground based telescopes. (~800)
  - A couple of years ago J. Catanzerite and I wrote a paper extrapolating eta_Earth from Kepler data (3~5%). A quick look at a more complete set of Kepler planets (1 yr later) yields an estimate 6~8%. These results are slightly controversial.
  - Not controversial is ~5% of stars have Jupiters. And in >1yr orbits ~2%. **~98%** of stars will **NOT** have a AFTA detectable Jupiter.
- It would be a waste of valueable telescope time for AFTA (cor) to attempt a "search" for undiscovered Jupiters.
- A RV planet orbit has 2 unmeasured angles (Orbit inclination, and rotation about, LOS).
  - But decreasing time for spectra from 99% to 96% is not important
- Two of the coronagraph concepts have < 2π az dark hole. (VNC, Shaped pupil) This should not be important.

VNC, Davinci Version

- VNC is nominally only affect by the Geometric loss from obscurations. There is no “multiplier”.
- Original XY shear has too low lyot throughput (with secondary)

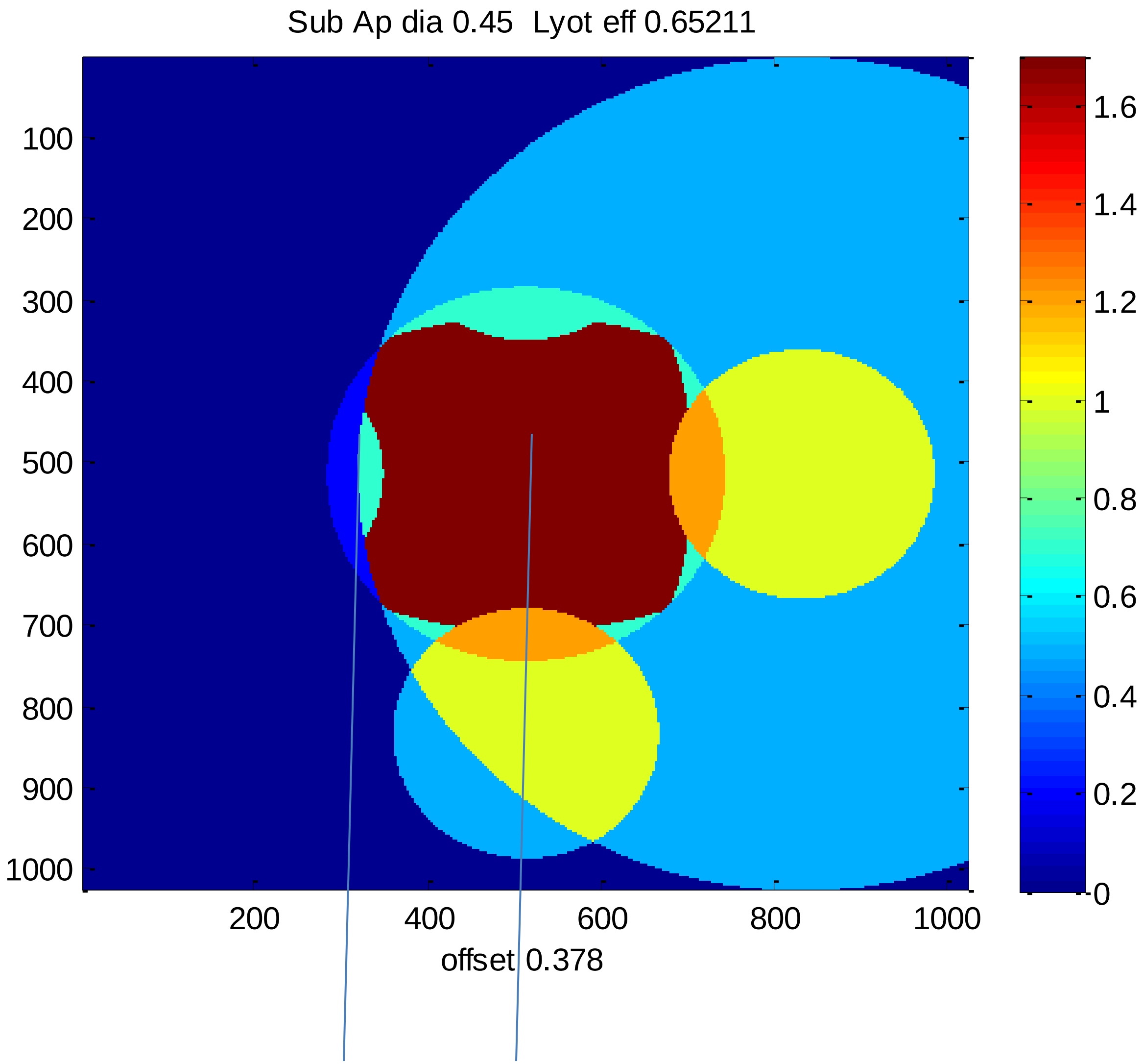




For a shear the has ~50% transmission @ 2.5l/D, the secondary obscuration blocks a large part of the pupil.
~28% lyot efficiency

The resulting Planet PSF is not so good. <<80% of light is in central lobe.

- DAVINCI concept originally described in a paper by Guyon, Shao, for a telescope with a secondary and 2 spiders (@90deg) Subsequently adopted to a concept using 4 separate telescopes. Now adopted to AFTA.



Very near optimal placement
Of subapertures

Secondary = 0.3 *primary

Subaperture dia 0.45*primary
Offset = 0.378 in X in this
drawing

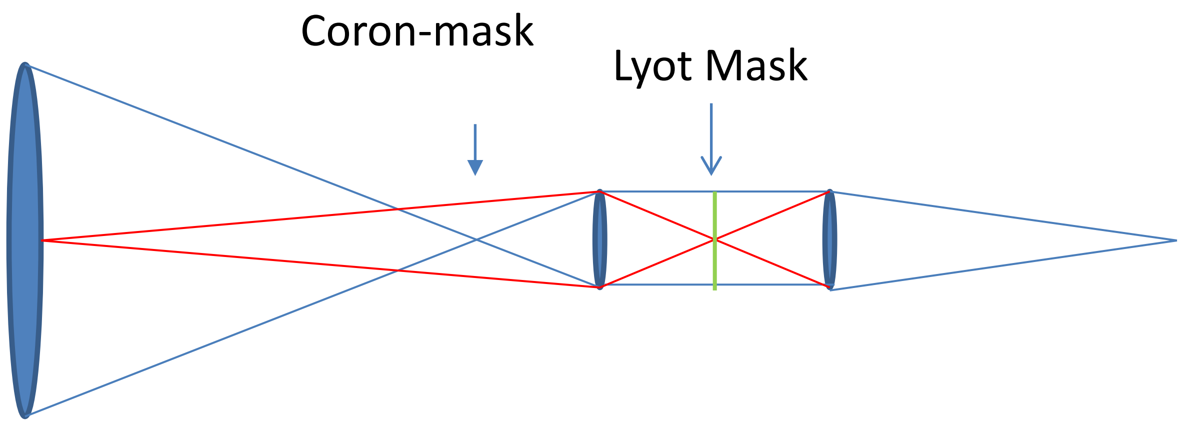
This fig is rotated 45 deg with respect to Hong/Bertrand

Total lyot efficiency 65.2%
(spider loss not included)
Each spider 2.5% of primary dia

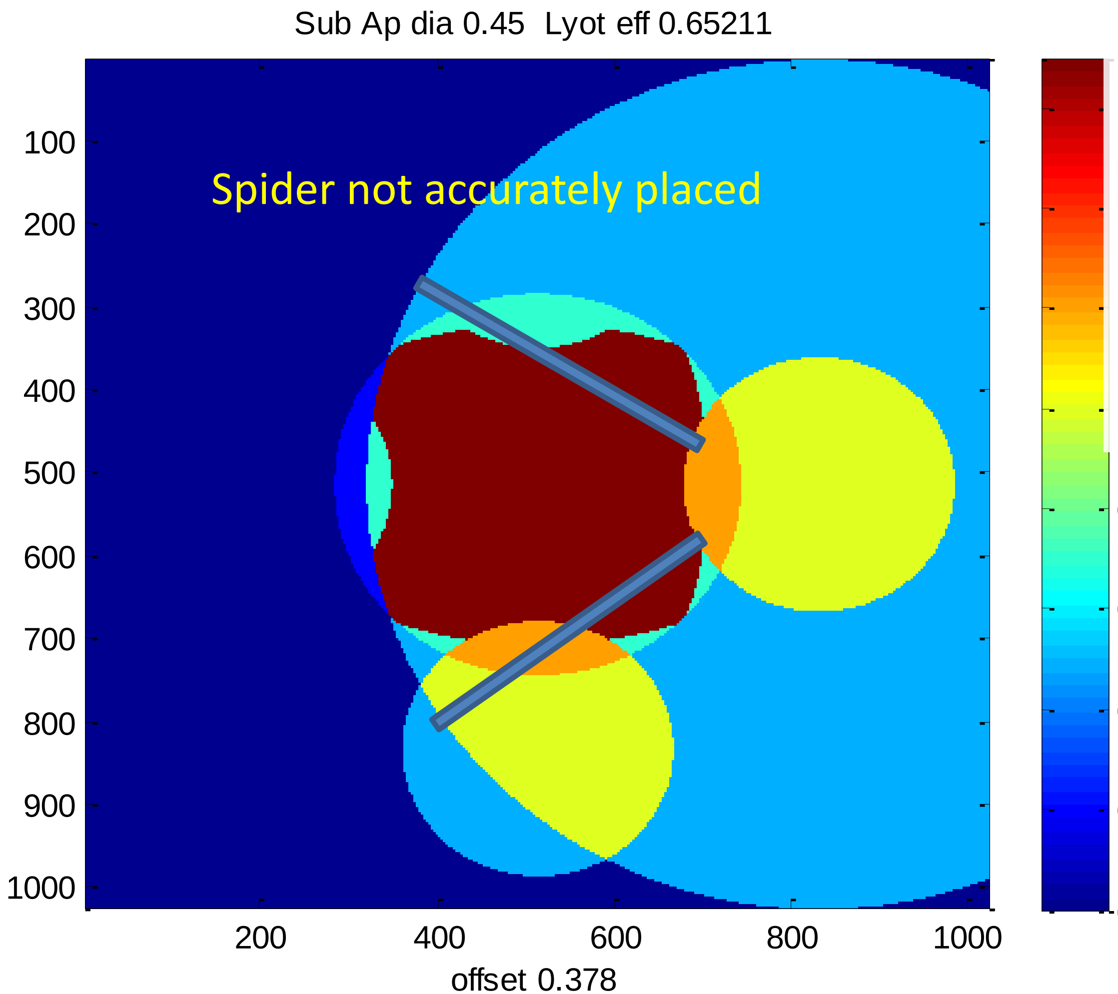
Distance of sub-center from edge of 2.4m aperture 0.378 of radius. Radius of sub-ap is 0.45 of primary

Exit pupil close to a filled aperture, **compact PSF**

Pupil Obscurations at the Lyot Mask

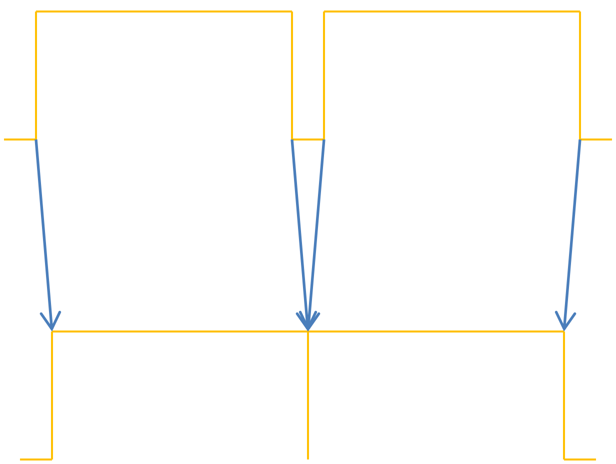


- If there is no coronagraphic mask, the pupil, including secondary and spiders are in sharp focus at the lyot plane.
- The existance of a coronagraphic stop results in features in the pupil "widening" at the lyot mask. (a band limited mask limits the amount "widening" but it's still significant)
- In a VNC, there are no masks at an image plane to diffract the starlight. **No** intentional **obscurations** between the telescope primary and the lyot stop.



Many of the new ideas are useable only for one of the coronagraph concepts. But ACAD, the use of extreme PIAA to remove the spiders, is a concept that can apply to all of the coronagraph concepts. Including VNC.

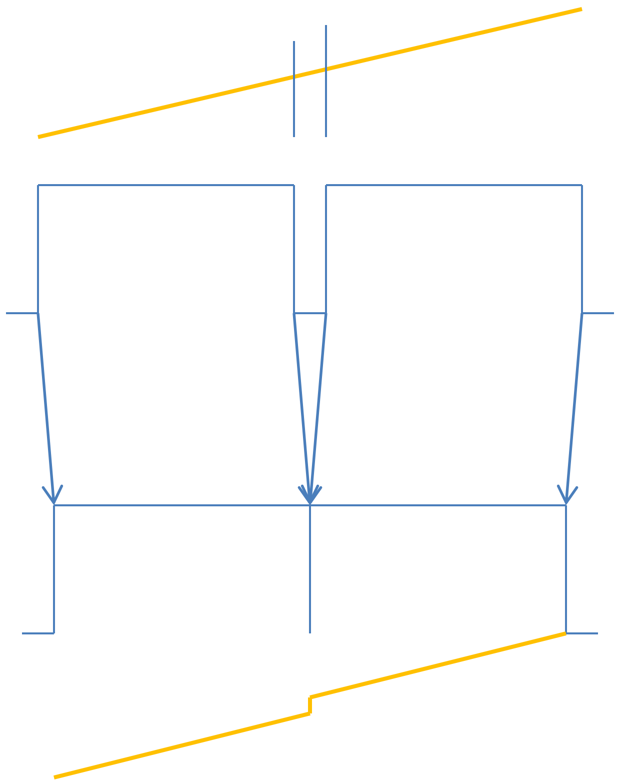
Would the VNC benefit from the use of ACAD?



A simplified explanation how PIAA can be used to remove the spider

Spider Removal, Side Effects

- ACAD in geometric optics can remove the spider for on axis starlight.
- But offaxis, the removal of the spider results in a phase discontinuity in the wavefront.
- 1mas offaxis (edge of star) produces a 0.3nm phase discontinuity. Since a star's diameter is ~ 1mas, achieving 1e-9 optical contrast will be more challenging.
- ACAD likely also makes the system much more sensitive to **<u>Low Order wavefront</u>** errors. An issue that is more important for AFTA than the original TPF-C.



OPD discontinuity = θ * Width_spider
θ is the off axis angle , Width = ~6.3cm

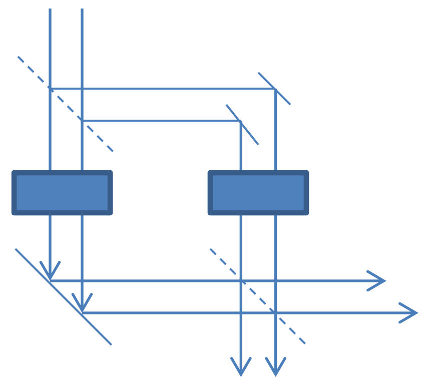
If θ is 1 mas, OPD = 0.3 nm
Phase ~ 3.5 mrad => 2e-6 null.

ACAD produces a θ^2 null

For VNC (and others) achieving contrast < 1e-8 (with a finite dia star) may be impossible if ACAD is used.

Davinci-VNC is interferometry of 4 non-overlaping apertures

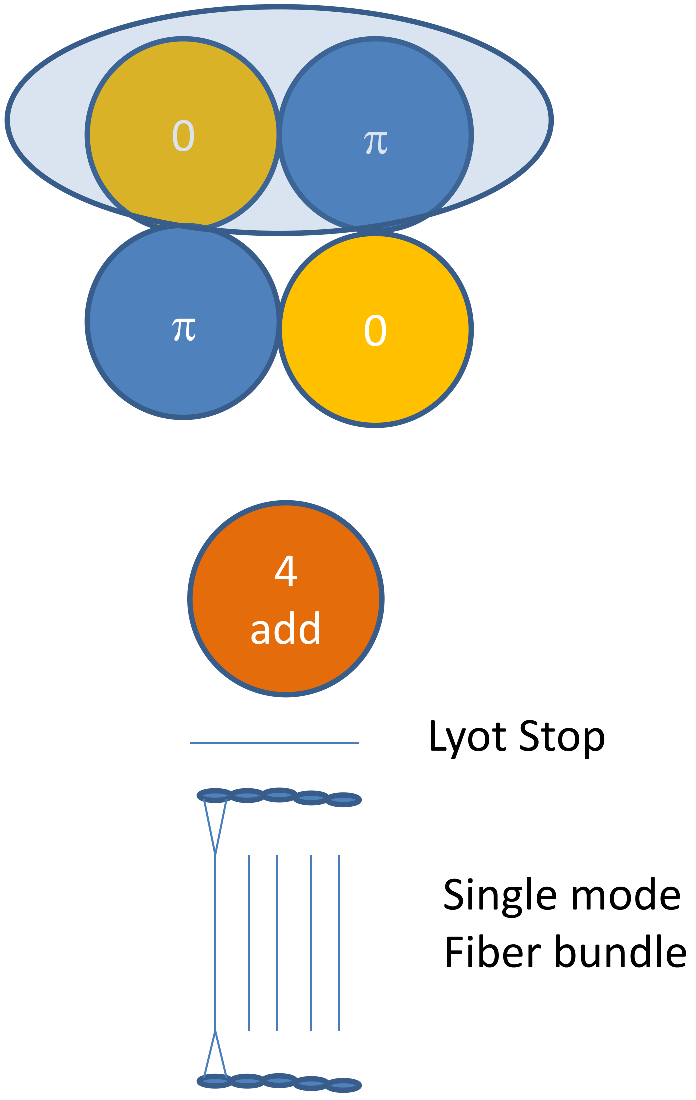
- Concept Geometry
  - Fully symmetric Machzender interf
  - @0 opd the MZI is achromatic and polarization insensitive.
  - π phase shift needs "glass" to produce achromatic null, over a finite bandwidth
  - 1e-9 contrast over >~20% possible with 2 glass design.
    - Thickness have to change by 10's ~100nm to shift the center of the visible spectrum.



- Fully symmetric means
- Same # reflections of identical surf at the same angle of incidence.
- Same # transmission through glass and AR coatings

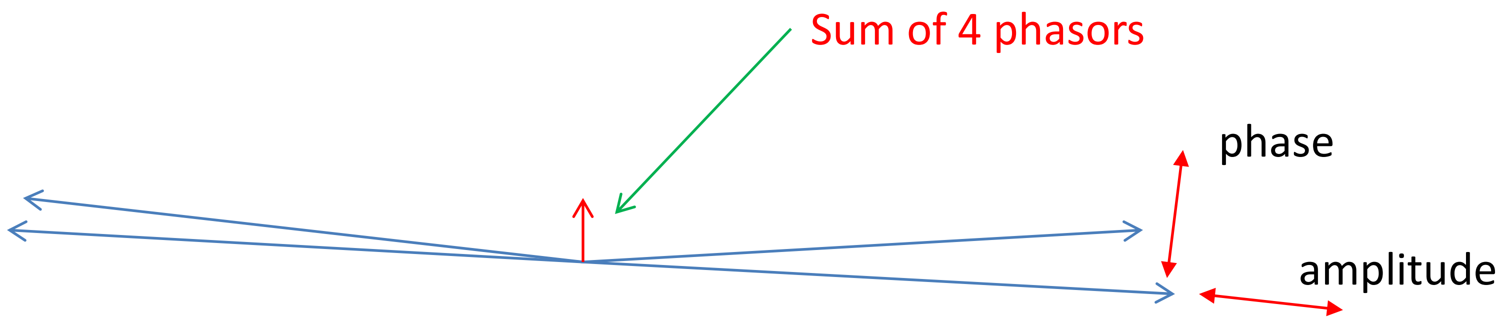
4 beam Nuller

- First null in X direction, followed by a 2nd stage nuller in Y direction.
- After the 2nd nuller, optics reforms a pupil at the lyot stop where the spiders are blocked.
- Since there is no focal plane mask, features in the pupil (secondary obscuration and spiders) are not diffracted.
- When the light enters the single mode fiber, the E field is specified by 1 complex number (Amp, phase)
  - The sum of the E field from the 4 apertures must equal zero.
- Phase control is accomplished by piston motion of the DM. Amplitude control is done by tip/tilting the light into the fiber.



Null Sensing and Control

using Post Coronagraph Interferometer



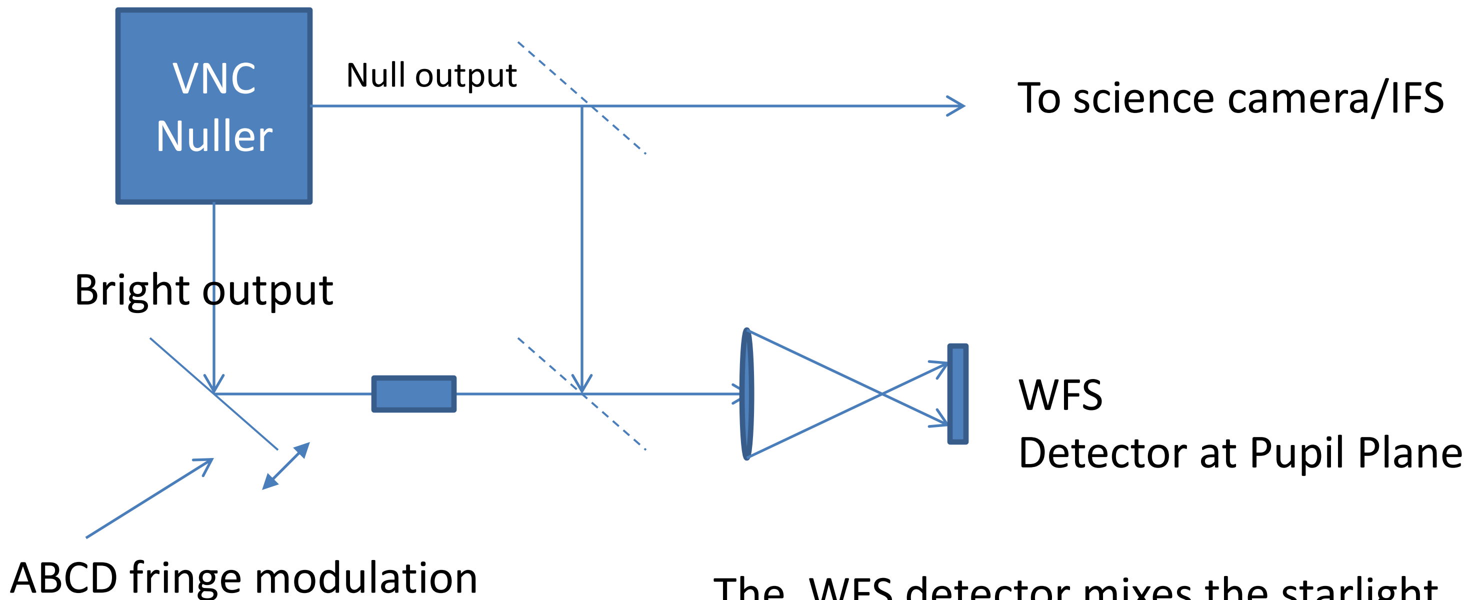
1) The 4 subspertures each provide an E field, phase and amplitude (phasor) into the single mode fiber. For a null, the 4 phasors has to add to zero.
2) Phase changes the angle of the phasor vector, amplitude the length.

3) Initially the 4 phasors, 2 will be roughly π out of phase with the other two but there will be both amplitude and phase errors in each of the 4 beams.

4) We know that if we piston that segment's DM, we will rotate the phasor. If we tip/tilt the DM we will change it's amplitude (coupling eff into the fiber).

5) However the initial tilt error into each fiber (from each of the 4 subapertures is unknown) An initial amplitude sensing dither is needed to calibrate d_amp/d_tilt.

Schematic - Wavefront Sensing for VNC-Davinci



Single actuator with high accuracy is used to provide phase diversity The "nulled" output is measured **<u>without zodi noise or CCD read noise</u>** because of heterodyne gain.

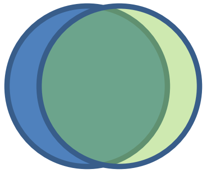
The WFS detector mixes the starlight rejected by the nuller with the "dark" light. The output of each fiber goes to a different pixel(s). It measures the E-field in the fiber (sum of all 4 inputs)

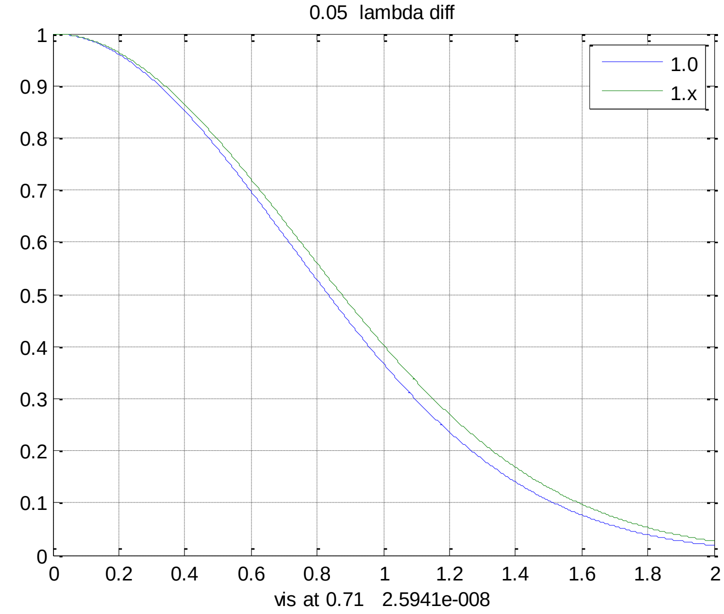
Chromatic Effects

- Most of the Phase errors are due to imperfect optics, that produce an OPD error. OPD errors are achromatically corrected by the DM.
- Most amplitude errors are caused by wavefront errors “Not” at a pupil, resulting in phase to amplitude conversion.
  - This is mostly a geometric effect and is achromatic.
  - However our amplitude correction, by reducing the coupling into SM fibers is not achromatic.
  - Depending on the amount of amplitude correction needed, this will more or less limit the bandwidth over which 1e-9 contrast is achievable.
  - ~20% bandwith should be achievable with an “optimized” VNC design.

Details on Amp Correction

- We control amplitude of light in the fiber by misaligning the spot on the fiber core.
- The mode field dia is λ dependent. A given tilt(urad) results in a different amount of attenuation at different wavelengths.
- If we have to correct for a large intensity balance in the two arms, we will only be able to do that over a narrow bandpass.
- From J. Krist, the amplitude variations due to Talbot effect dominate at the 1st reimaged pupil and are ~0.3% rms.

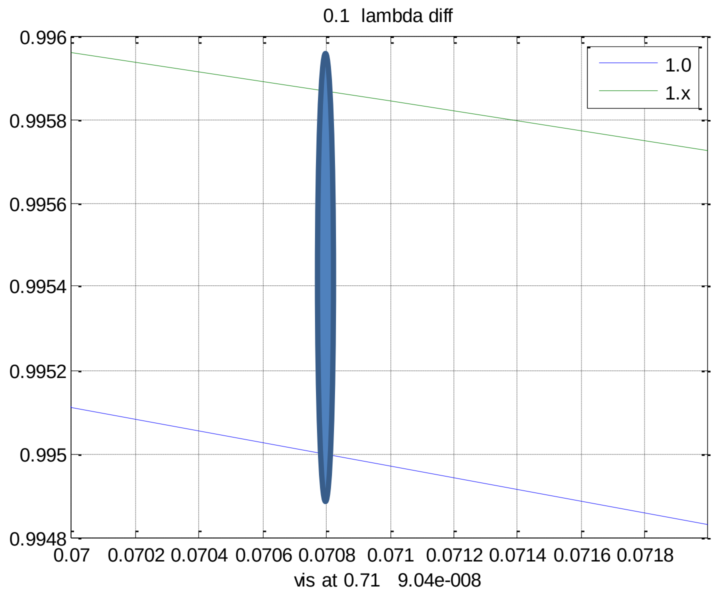




Mode field of SMF at two λ different by 5%.

Bandwidth Limit Using Fiber Amp Control

- Attenuating the light by 0.5% at one wavelength results in a 0.45% at a 10% longer wavelength.
- A 0.08% intensity mismatch
- This mismatch results in leakage that is ~5e-8 at the edge of a +/-10% bandpass.
- This leakage is a diff limited image at the location of the star. The contrast at the 1st airy ring is ~1/50 lower ~1e-9.
- **Averaged over a +/-10% bandpass the leakage is ~5e-10 at the 1st airy ring.**



Inten mismatch

Leakage ~ $\delta I^2/16$

Phase err

Leakage ~ $\delta\phi^2/4$

SNR in Wavefront Sensing

- The post coronagraphic interferometric wavefront sensor is much more efficient in measuring the Efield at the output of the VNC than other techniques based on image diversity from Poking the DM.
- Measurement is limited by photon noise from the star, not the local&exo-zodi.
- The interferometer moves 1 mirror in 1 arm of the interferometer to dither the phase. And that mirror can be monitored by a “local” sensor with picometer resolution.
  - The diversity of the multipixel wavefront sensor can solve for errors in the motion of that mirror. (Piston/tip/tilt)
- The DM in only used to incrementally improve the amp/phase inside the SMFs. The DM is never used to provide a 15nm dither with the expectation that there is no unintended 15picometer motion.

SNR Numerical Example

- Vis band 0.55um 20% bw.
- Integration time needed to geneate 6e-10 contrast

V 20% 0mag	1.19E+10phot/s/m2 20%		
star mag	**7**	**5**	
Total QE	0.5	0.5	
area	0.04	0.04	m2
det phot/s	378,555	2,388,519	phot/s
Null depth	3.00E-08	3.00E-08	
Contrast @1airy	6.00E-10	6.00E-10	
rms phase err	4.90E-05	4.90E-05	
#phot needed	8.33E+08	8.33E+08	
# sec integ	**2,201**	**349**	Seconds

At Princeton workshop,
S. Shaklan presented a time
Estimate for speckle nulling
To produce a 1e-9 dark hole
for a 5 mag star.
~8hrs (zodi limited 1e ccd
Read noise)

For zodi limited mid-freq
wavefront sensing, going from
5 mag to 7mag means going
from 8 hrs to ~320 hrs.

Speckle Subtraction

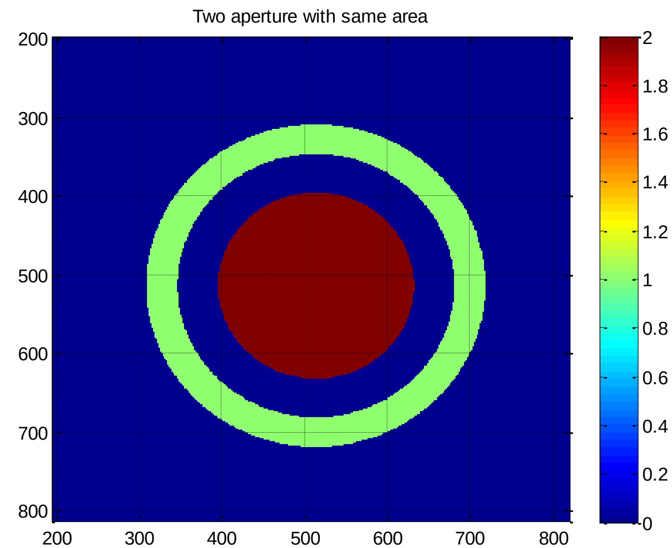
- Concept
  - Measure the E field at the pupil after the coronagraph.
  - FFT^2 to estimate the residual speckle pattern(speckle PSF).
- Advantages
  - SNR, the speckle PSF estimate **doesn’t have phot noise from local and exo-zodi.** (Noise in the planet image is dominated by photon noise of local/exo-zodi)
  - **The PSF estimate has Zero time lag**. The speckle estimate is made simultaneous with the science data. We don’t have to assume the speckles are stationary for 10 hrs or 200 hrs.
- Requirements are modest (if we achieve a raw contrast of 1e-9) we need to subtract the 1e-9 speckles to 2e-10 to detect a 1e-9 planet. 20% accuracy in speckle subtraction (from systematic errors).
  - To be validate initially by simulation.

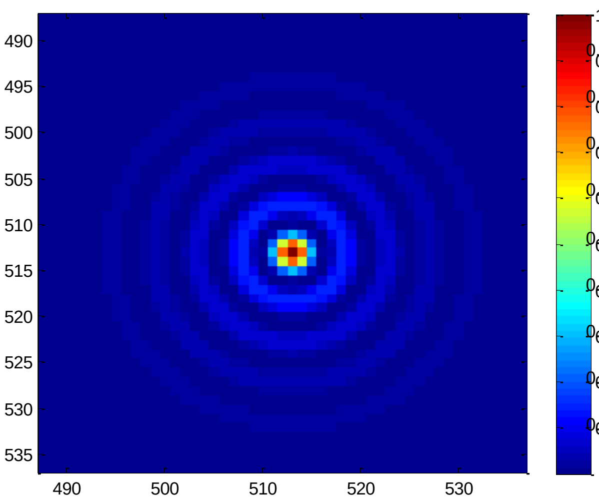
Comment on Speckle Stability

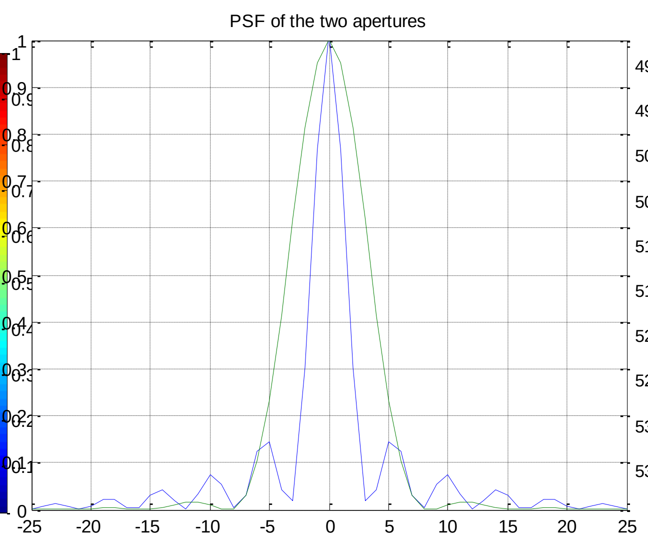
- Wes Traub did a calculation of speckle stability assuming there was NO leakage of low order wavefront errors into the dark hole. He calculated how warping of the mirror would produce speckles in the dark hole. (assuming the DM's completely remove the original WFE in the telescope)
  - Speckle ~ (change residual error)^2 more realistically the DM's are not perfect in achieving 1e-15 contrast.
  - Change in the speckles ~ residual_Err*Change_err, change has to be < 2e-10 to detect a planet at 1e-9. (speckle pinning?)
  - Leakage from low order to mid-freq is very coronagraph dependent. In Wes's calculation 10mas tilt would not produce speckles > 1e-12 at > 3 λ/D. None of the coronagraphs work with a 10mas tilt error.
- Leakage from low order to mid-freq varies strongly between coronagraph types.
  - In general Coronagraphs with small IWA's are more sensitive to LoWFEs
  - But also coronagraphs that have $\boldsymbol{\theta^2}$ nulls are much more sensitive than those with $\boldsymbol{\theta^4}$ nulls. Before AFTA, all coronagraphs were θ^4. But any coronagraph that uses ACAD, now has a θ^2 null.

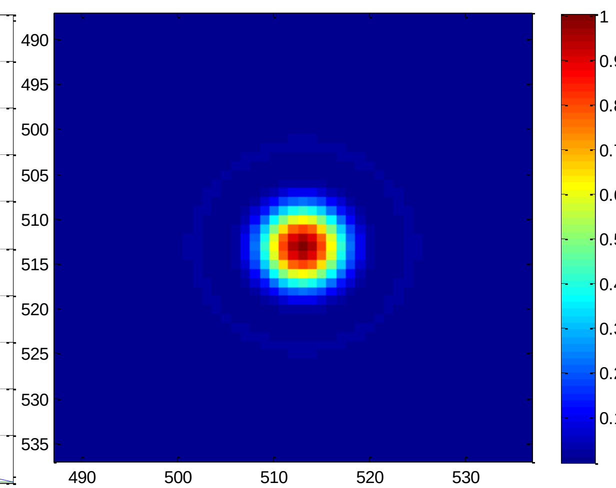
Compact Aperture (Planet Image)

- Two aperture, with the same total area. (~33% of the filled green circle)
- The total flux in both PSF's are the same.
- The peak flux (photons/arcsec2) the same
- % flux in central lobe
  - **Compact aperture ~83%**
  - **Ring aperture ~15% in central lobe**
  - **Ring aperture ~34% < 1st ring**









SNR, Speckle Sub, Spectroscopy

Detecting a Planet

zodi	4	
local+Exo	20.5	mag/as^2
	0.55	lambda um
Exitpupil Dia	0.96	meters
lyot area	2.49	m^2
lam/d	5.73E-07	radians
	0.118	arcsec
zodi	37.86	det phot/m^2
zodi/(l/d)	1.32	phot/s
planet	1.00E-09	planet contrast
parent star	7.00	mag
planet mag	29.50	mag
total P flux	0.019	phot/s
% in central lobe	0.80	
Planet signal	1.51E-02	phot/s
Integ time sec	180,000	sec
	50	hrs
SNR	5.57	

This is SNR=5.6 in 20% bw
SNR =10 in 2% BW 40X longer
Multiply by 2 for efficiency of IFS
And spectroscopy is hard.

If speckle subtraction is done by subtracting two images (limited by zodi) the SNR of each Image for a 1e-9 speckle has to be 7 for the Difference to have a noise of 2e-10

This means **200hrs** of observation for zodi limited speckle subtraction (eg ADI rotating telescope)

VNC speckle subtraction **1hr**

Key performance parameters are in blue

1. % light in central lobe of planet PSF
2. Lyot efficiency

If the lyot efficiency drops frm 55% to 27% it will take 400hrs. If in addition the % light in the central lobe of the Planet PSF drops from 80% to 40% Integ time => **800hrs**

~ 1 month to do speckle subtraction

VNC Summary

- Good Lyot Efficiency **(55~60%)**
  - Dark hole not 2π in azimuth (like Shaped pupil, linear BL Lyot) This is not important for a mission the concentrates on spectroscopy of “known” Jupiter/saturns.
- Amplitude and phase control with ~20% bandwidth at a time
- Compact exit pupil (~80% energy in central lobe) Critical for **spectroscopy.**
- θ^4 null, will not use ACAD (θ^2 leakage)
- Telescopes stability requirements should be calculated as $\theta*\delta\theta$ not $(\delta\theta)^2$
- Wavefront sensor immune to Local/Exo-Zodi noise
  - Wavefront sensing in 350sec (5 mag), 2200sec (7 mag)
  - (From Shaklan @ Princeton Workshop speckle nulling ~8hrs on 5 mag star=> 320hrs for 7 mag star)
  - Wavefront sensing that is zodi limited falls off a cliff > ~5mag.
- Speckle subtraction immune to Local/Exo-Zodi noise, photon noise is photon noise of the starlight. 200 hrs vs 1hr

Backups

Amplitude Mismatch from Asymetrical Diffraction

- Relay optics relay the pupil of the telescope to the DM. From a geometric optics point of view, there are no vigneting edges between the DM and the Lyot stop.
- However the pupil is divided into 4 parts then recombined. The intervening optics are NOT infinitely oversized. In addition when the pupil is split up, the limiting aperture (beyond the geometric footprint) is asymetric. This asymetry gives rise to a differential talbot effect that can increase the amplitude difference in the 4 beams (beyond the 0.3% from the AFTA telescope).
  - The solution is to place limiting apertures (that are outside of the geometric beam) that symetrizes the diffraction in the 4 beams.
- There may or may not be enough time between now and Nov 10 for the VNC modeling folks to do this. (In large part due to extended vacations planned long ago)